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An S-Band Reflection-Type Phase Shifter - A Design Example Using Ferroelectrics

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ABSTRACT

One of the challenges faced in using ferroelectrics in high frequency devices is how to effectively use the material in a circuit design. A compact reflection-type phase shifter fabricated on sapphire substrates coated with ferroelectric barium strontium titanate (BST) thin-films has been built which shows the promise of using BST thin films in the design of tunable microwave devices. The phase shifter, fabricated as one monolithic assembly, consists of a 3dB coupler, meandered line inductors and tunable interdigital capacitors. A continuously variable phase shift range of more than 100° using the branch-line coupler was obtained at a center frequency of 2.95 GHz, and more than 90° phase shift over 200 MHz bandwidth with a bias voltage range from 0 V to 175 V. The phase shifter using the Lange coupler has over 700 MHz bandwidth centered at 2.2 GHz with a phase shift of more than 90° and an insertion loss less than 2 dB and return loss of greater than 14 dB, over a bias voltage range from 0 V to 160 V. The loss of the BST phase shifter presented in this work is on the order of other commercially available RF front-end components, such as bandpass filters and RF switches. This holds promise for the practical realization of smart antenna systems in cellular handsets and wireless LAN cards.

INTRODUCTION

With the recent increase in market demand for mobile communications devices, there has been added pressure to minimize the size of microwave components, such as filters, couplers and phase shifters. It has been known that the high dielectric constant and electric field dependence of ferroelectric materials, such as strontium titanate ($SrTiO_3$) and barium strontium titanate ($Ba_xSr_{1-x}TiO_3$), allow for miniature tunable microwave components [1]-[6]. In addition, ferroelectric-based phase shifters have several advantages over *pin* diode and ferrite phase shifters: monolithic integration, fast speed of tuning and much lower control-line power dissipation [5]. The phase shifter presented in this paper is a fully integrated monolithic device. All components are fabricated directly on the BST coated substrate. The design was targeted for S-Band operation to demonstrate the ability of this technology to achieve good low frequency phase shifter performance in a small volume.

Coplanar waveguide (CPW) structures are used to confine electric fields near the substrate surface, keeping a large percentage of the electric field in the BST, hence maintaining a high effective dielectric constant and a large tunability. A thick copper (Cu) metallization process, adopted from MEMS techniques, is used to minimize conductor losses in the distributed elements [7]. Air bridge crossovers are also used to connect ground planes and suppress spurious modes. Two identical LC networks are connected to a coupler to achieve the phase shift. The integrated approach described herein allows better performance than a discrete approach in that phase shifter networks fabricated on one substrate are well matched, thus improving return loss.

SUBSTRATE FABRICATION

Barium strontium titanate (BST) thin films were prepared by MicroCoating Technologies (MCT) using their patented, open-atmosphere combustion chemical vapor deposition (CCVD) process [8]. Since the investigations will be carried out at room temperature, a composition of $Ba_{0.6}Sr_{0.4}TiO_3$ was used so that the material would be operating in the paraelectric phase where a large change in ε_r with respect to bias voltage would occur. The barium to strontium ratio gives an expected Curie temperature of −10°C. For this investigation, a single crystal aluminum oxide substrate was selected resulting in BST with a <111> orientation. A variety of material analytical techniques were used to determine the physical properties of the film samples. X-ray diffraction (XRD) was performed on all samples, θ-2θ scans, see Figure 1, to determine the crystal structure of the deposited films. Film surface morphology was examined using optical profilometry, Figure 2 (a), and scanning electron microscopy, Figure 2 (b). These analyses showed a smooth, dense-appearing uniform film. The thicknesses of $Ba_{0.6}Sr_{0.4}TiO_3$ and sapphire were 0.45 μm and 430 μm, respectively. A bulk BST dielectric constant of $\varepsilon_r = 800$ was found to give the best fit to measured data of CPW line using electromagnetic field simulation using the Microwave Office^{TM}.

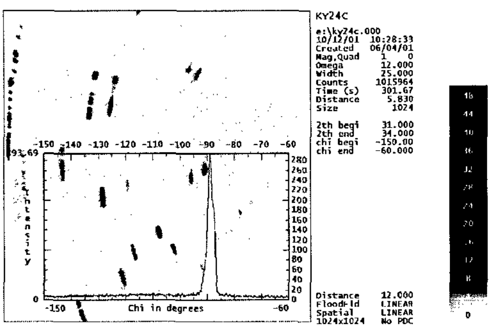
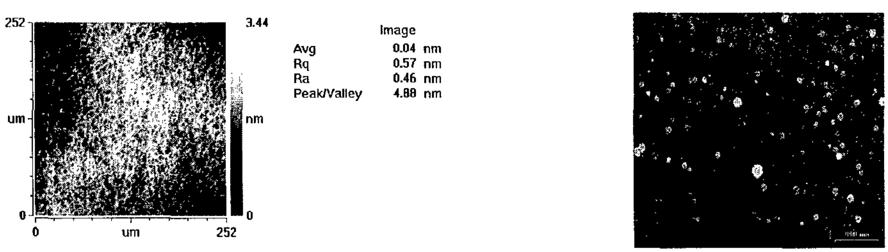


Figure 1. Representative XRD analysis θ-2θ scan.



(a) (b)

Figure 2. Film surface. (a) Representative optical profilometry map and (b) Representative scanning electron microscope micrograph.

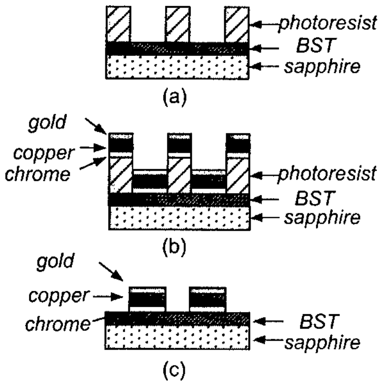


Figure 3. Metallization processing of the BST/sapphire substrate.

The metallization processing of the substrate is shown in Firgure 3. 200 Å of chrome deposited as an adhesion layer after patterning a thick photoresist layer. On top of the chrome, $2.7 \mu m$ of copper was deposited to form the main conductor layer with a cap of $0.3 \mu m$ of gold as an oxidation barrier for the copper. A lift-off process was then used to create the metal pattern on the substrate.

CIRCUIT DESIGN AND EXPERIMENTAL RESULTS

The schematic of the reflection-type phase shifter is shown in Figure 4. Because 90° phase shift increments may be switched in using quadrature hybrids, 90° is the minimum range of phase shift needed from a variable phase shifter. A 3-dB branch-line coupler was designed using meandered lines instead of straight lines in order to reduce total size of the phase shifter [9]. The 3-dB coupler is combined with two identical LC networks and bias network. The photomicrographs of the phase shifter using the branch-line coupler and the Lange coupler are shown in Figure 5.

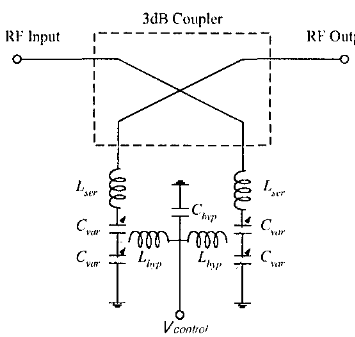
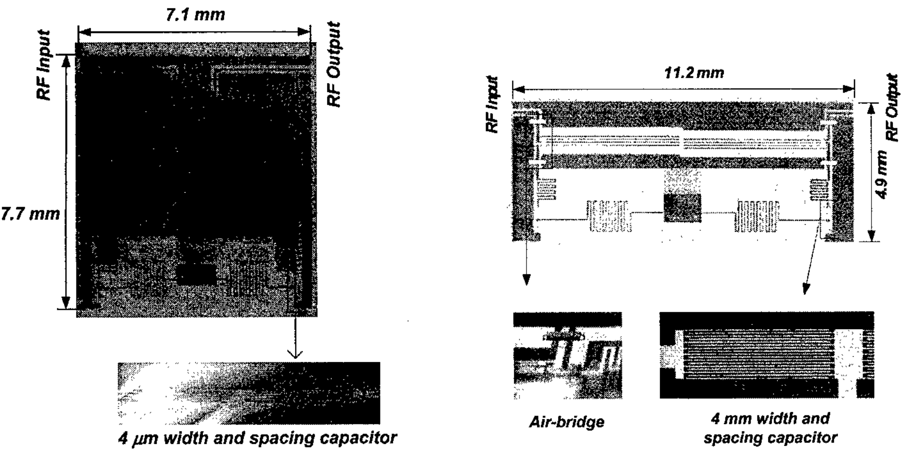


Figure 4. Schematic of the reflection-type phase shifter.



(a) (b)

Figure 5. Photomicrograph of the reflection-type phase shifter, air-bridge, and 4 μm interdigital capacitor using (a) the branch-line coupler (b) the Lange coupler.

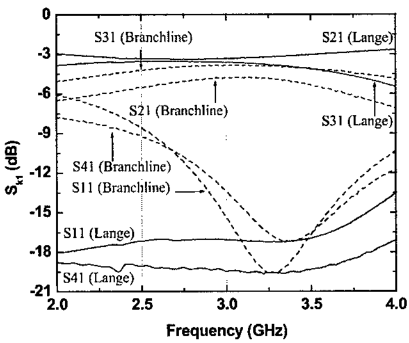
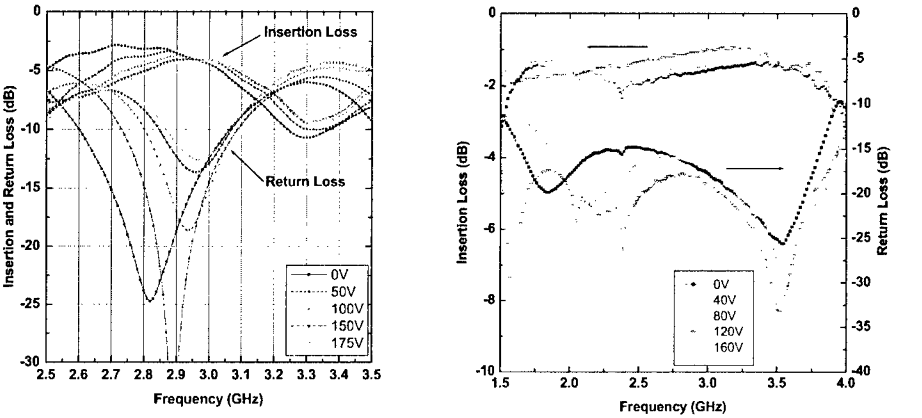


Figure 6. Measured results of the branch-line coupler and the Lange coupler.

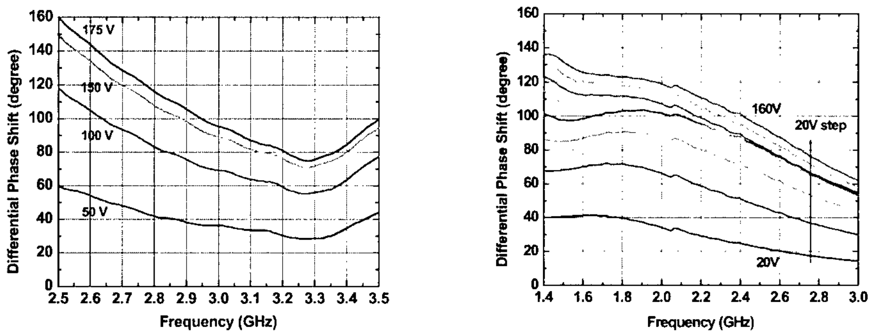
S-parameters of the branch-line coupler, the Lange coupler and the phase shifter were measured using HP8753C network analyzer and Cascade Microtech ground-signal-ground microwave probes. S-parameters of the couplers as a function of frequency are shown in Figure 6. Magnitudes of signals at direct and coupled ports of the branch-line coupler at 3 GHz are 4.7 and 3.8 dB, respectively. The return loss and isolation are greater than 13 dB between 2.96 and 3.73 GHz. The Lange coupler has 3.5 ± 0.5dB in the range of 2-3.4 GHz or 52% for 1-dB amplitude balance. In addition, the isolation is greater than 18 dB, and voltage standing wave ratio (VSWR) is less than 1.4 in the same frequency range. Therefore, the Lange coupler has an advantage over the branch-line coupler because of larger bandwidth. The insertion and return loss of the reflection-type phase shifter are shown in Figure 7. The most equal insertion loss of the phase shifter using the branch-line coupler for all bias levels occurs at 2.95 GHz and is between 4.0 and

4.2 dB over the bias range. The insertion loss is less than 5 dB between 2.83 GHz and 3.03 GHz, with a variation of no more than 2 dB. The return loss is greater than 12.5 dB at 2.95 GHz, and greater than 10 dB over a range 200 MHz as shown in Figure 7(a). Except for the narrow band resonance associated with the Lange coupler isolation response at 2.35 GHz, the maximum insertion loss is 2 dB between 1.6 GHz and 3.7 GHz with all bias states in Figure 7(b). Also, the return loss is greater than 14 dB in the range of 1.85-3.8 GHz.



(a) (b)

Figure 7. Insertion loss and return loss versus frequency (a) using the branch-line coupler (b) using the Lange coupler.



(a) (b)

Figure 8. Differential phase shift with respect to phase at 0V using (a) the branch-line coupler (b) the Lange coupler.

Figure 8 shows the relative phase shift with respect to the phase at 0V. About 110° phase shift was achieved at 2.85 GHz over a 0V to 175 V range and more than 90° was achieved over ± 100 MHz about 2.95 GHz using the branch-line coupler as shown in Figure 8(a). Also, more than 136° phase shift is achieved at 1.42 GHz and more than 90° between 1.85 and 2.56 GHz with a

bias voltage of 160 V using the Lange coupler. The BST reflection-type phase shifter has maximum 89°/dB at 1.87 GHz and greater than 44°/dB in the range of 1.52-2.56 GHz with a bias voltage of 160 V.

CONCLUSION

A monolithic reflection-type phase shifters using the branch-line coupler and the Lange coupler on $Ba_{0.6}Sr_{0.4}TiO_3$/sapphire were designed, fabricated and tested. Experimental results showed more than 90° phase shift was achieved at 2.95 GHz over ± 100 MHz range using the branch-line coupler. Also, the phase shifter using the Lange coupler has a phase shift range of more than 90° with an insertion loss of less than 2 dB and a return loss of greater than 14 dB in the frequency range of 1.85-2.56 GHz over a bias voltage range from 0 V to 160 V. The maximum 89°/dB was achieved at 1.87 GHz with a bias voltage of 160 V.

ACKNOWLEDGEMENT

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